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Prolongation of soil frost resulting from reduced snow cover increases nitrous oxide emissions from boreal forest soil

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Emission rates of the greenhouse gas, nitrous oxide (N_2O), from northern upland forest soils are generally low. According to recent climate scenarios, the snow cover in the boreal region is predicted to decrease and which will result in lower soil temperatures. In this study, we investigated whether lower soil temperatures during winter can also trigger N_2O emissions from boreal forest soils with originally low N_2O emissions, as has earlier been shown for northern agricultural soils with higher N_2O emissions. We measured the N_2O emissions from a spruce forest in eastern Finland where the soil temperature was changed by manipulating snow-pack thickness and using insulating covers. The effects of the treatments on methane (CH_4) and carbon dioxide (CO_2) fluxes were also studied for comparative purposes. The results show that there can be an increase in N_2O emissions and CO_2 production rate from boreal upland forest soils resulting from a thinner snow cover that causes a prolongation of soil frost. Reducing the snow pack thickness had only minor effects on the CH_4 fluxes.

Introduction

Nitrous oxide (N_2O) is 298 and methane (CH_4) 25 times stronger a greenhouse gas than carbon dioxide (CO_2) with a 100-yr time horizon (Solomon *et al*. 2007). N_2O is produced in soil mainly through nitrification and denitrification processes and its production rate is controlled by several factors, such as the availability of oxygen, mineral nitrogen and microbial carbon substrates, and temperature and soil moisture (Davidson 1991). N_2O emission rates from N-limited boreal upland forest soils are generally low as compared with those from e.g. temperate and tropical forest soils or boreal agricultural soils (Klemedtsson *et al*. 1997, Simpson *et al*. 1997, Syväsalo *et al*. 2004, Brumme *et al*. 2005, Pilegaard *et al*. 2006).

According to several studies, a large amount of N_2O can be produced and emitted from soils at low temperatures, even below 0 °C (Holtan-Hartwig *et al*. 2002, Öquist *et al*. 2004, Koponen *et al*. 2004, Groffman *et al*. 2006, Maljanen *et al*. 2007). Emissions of N_2O during winter may account for more than one half of the annual emissions in boreal and temperate regions (e.g. Röver *et al*. 1998, Teepe *et al*. 2000, Schürmann *et al*. 2002). However, the reasons for the high N_2O emissions during winter and the production of N_2O in frozen soils are not well understood. Studies on N_2O emissions from boreal forests, especially during cold periods, are lacking despite the fact that these forests cover extensive areas in the northern hemisphere (23.48×10^6 km^2; Brumme *et al.* 2005).

CH_4 is produced in soils by anaerobic methanogenic microbes and consumed by aerobic methanotrophic bacteria (Le Mer and Roger 2001). Well-drained forest soils are globally important sinks for atmospheric CH_4, since the sink strength (about 30 Tg CH_4) is similar to the annual increase (22 Tg CH_4) in atmospheric CH_4 (Le Mer and Roger 2001, Solomon *et al.* 2007). Northern ecosystems, including forests, have been considered as sinks of atmospheric CO_2. The sink strength, however, is sensible to global warming (Piao *et al.* 2008). Furthermore, the fate of soil carbon plays a key role in the carbon balance of forest ecosystems.

Snow insulates the soil during winter, therefore a reduced snow cover enhances soil freezing, lengthens the freezing period, and results in soil freezing to gretaer depths (Schürmann *et al.* 2002, Groffman *et al.* 2006). According to recent climate scenarios, the snow cover in the boreal region is expected to decrease (Solomon *et al.* 2007), thereby resulting in lower soil temperatures. Our hypothesis is that a reduction in the thickness of the snow cover which causes deeper and prolonged frost would increase N_2O emissions from boreal upland forest soil, and also change the soil CH_4 and CO_2 dynamics. The release of CO_2 from the soil could decrease as a result of lower soil temperatures, and CH_4 uptake could either increase because of the decreasing diffusion barrier (snow cover) or decrease due to the lower soil temperatures.

Material and methods

Site description and soil temperature manipulations

The study was carried out in a 49-year-old Norway spruce forest (*Picea abies*) located in the boreal coniferous zone near the city of Joensuu, eastern Finland (62°36´N, 29°43´E, 84 m a.s.l.). The long term mean annual temperature is 2.6 °C and the long-term annual precipitation 609 mm, of which approximately one half falls as snow (Drebs *et al.* 2002). The average height of the tree stand was 17 m. The stand density was 864 trees ha^{-1}, stand volume 211 m^3 ha^{-1} and the basal area 25.4 m^2 ha^{-1}. The soil is glacial till and the pedological soil type ferric podzol. The organic matter (OM) content in the organic horizon was 70.8% and in the uppermost mineral soil layer (3–10 cm) 9.0%. The carbon to nitrogen (C/N) ratio in the organic horizon and in the uppermost mineral soil was 22.4 and 15.9, respectively. Soil pH (H_2O) in the organic horizon was 4.2 and in the mineral soil 4.4. The snow manipulation experiment was established in 2005 with three different treatments, and three replicate plots for each treatment. The snow manipulations were carried out in winters 2005/2006 and 2006/2007. The treatments were: (1) control (C), where the snow was allowed to accumulate and melt naturally, (2) open (O), where the snow was removed during winter in order to allow frost to pass deeper into the soil, and (3) frost (F), where the snow was removed during winter as in the O treatment, and the ground surface then insulated from the end of March to 4 July in order to continue the soil frost period. The insulation cover consisted of two plastic sheets with 15 cm of hay in-between. Each plot was 12 × 12 m.

Gas flux measurements

Fluxes of N_2O, CH_4 and CO_2 were measured simultaneously using a static dark-chamber method. Two types of chambers were employed. The first type consisted of a galvanized steel cylinder (diameter 30 cm, height 30 cm) with a gas-tight plastic lid with two holes closed with 25 mm rubber septa. The holes were opened and the sharp, lower edge of the chamber was twisted into the soil. This type of chamber was used only in March 2007. The second type of chamber was a similar steel cylinder with two 27 mm rubber septa in holes through the fixed steel cover. The septa were kept open when the chamber was placed on the soil, and were carefully closed at the start of the measurements. The chamber was air-tightly sealed to the ground with a rubber gasket attached to the lower edge of the cylinder, and a tight seal was ensured by placing a ca.

1 kg weight on top of the chamber. The air in the chamber headspace was mixed using a battery-operated fan fixed on the inside of the chamber top. When the gas fluxes were measured on the F plots the insulation cover was removed during the sampling period of 30 min. Before the covers were removed, five gas samples were taken below the cover at each sampling time in order to check that there was an accumulation of gases.

Gas samples (40 ml) were drawn from the headspace of the chambers with 50 ml polypropylene syringes (Terumo) equipped with a three-way stopcock (Connecta) 5, 10, 20, and 25 minutes after the chambers had been closed. In January 2008, the samples were taken after 15, 30, 45, and 60 min. In 2007 the gas samples were injected into pre-evacuated 12 ml Labco Excetainers® and analyzed with a gas chromatograph (Agilent 6890N) equipped with a GILSON auto sampler, flame ionization (FI) and electron capture (EC) detectors, and the flux rates were calculated from the linear change in the gas concentrations. Compressed air (Linde AG, Germany) containing 1.98 ppm CH_4, 396 ppm CO_2 and 0.389 ppm N_2O was used for calibration. The CO_2 flux measured *in situ*, termed here as CO_2 production, is the CO_2 flux from the respiration of soil microbes and fauna, the dark respiration of plants, and root respiration. The negative CH_4 flux from the soil to the atmosphere is termed here as CH_4 uptake.

The chamber measurements on two replicate subplots with three replicate chambers, including C, O, and F treatments, were performed nine times in 2007, the second year of the snow manipulation, between March and October and once in January 2008. Gas fluxes from the control plots in March 2007 and from all the plots in March and April 2008 were determined by measuring the gas concentration gradients from the snow, and by calculating the associated diffusion rates in the snow (Sommerfeld *et al*. 1993, Maljanen *et al*. 2003). Gas samples (40 ml) were drawn from the snowpack using a stainless steel probe (∅ 3 mm, length 50 cm). For calculating the diffusive fluxes, an ambient gas sample was taken above the snow pack and another sample inside the snow pack 2 cm above the soil surface. Additional gas samples were taken in the snow pack in order to check the linearity of the gas gradient. Snow samples were collected simultaneously with a PVC tube (∅ 10.2 cm) for porosity measurements. The intact samples were weighed and the average porosity of the snow calculated using the density of pure ice (0.9168 g cm^{-3}).

Gas samples taken in 2008 were analysed on a Shimadzu 14A GC equipped with FI, EC, and thermal conductivity (TC) detectors for CH_4, N_2O, and CO_2, respectively. The compressed air standard used with the Shimadzu gas chromatograph contained 1.81 ppm CH_4, 382 ppm CO_2, and 0.320 ppm N_2O, and the gas fluxes were calculated as described earlier.

Environmental variables

The air and soil temperature and volumetric water content of the soil were logged at 30 min intervals (CR10X-2M datalogger with AM 16/32 multiplexer, Campbell Scientific, Shepshed, UK). The temperature of the air (at a height of 2 m) and the soil (at depths of 5, 15 and 50 cm) were measured with Pt-100 thermistors and the soil moisture content by TDR (CS616, Campbell Scientific) at a depth of 15 cm.

Soil samples for the determination of NO_3^-, NO_2^- and NH_4^+ were collected from the organic horizon (0–3 cm) and from the uppermost mineral soil layer (3–10 cm depth) in June and in October 2007. NO_3^- was extracted from the soil with H_2O, and NH_4^+ with 1M KCl solution. NO_3^- and NO_2^- were analyzed by ion chromatography (Dionex DX-120) and NH_4^+ by spectrophotometry (Fawcett and Scott 1960).

Statistical analysis

Analysis of variance was used for investigating the soil parameters and in order to overcome the problems caused by the hierarchical structure of the data, e.g. measurements repeated in the same study plots, a Linear Mixed Model (SPSS 14.0) test was applied for the gas flux data in order to test the differences between the treatments. The study plots were set as random factors. The N_2O fluxes were log-transformed to normalize the distributions. Spearman non-parametric rank correlation was used to study the relationships

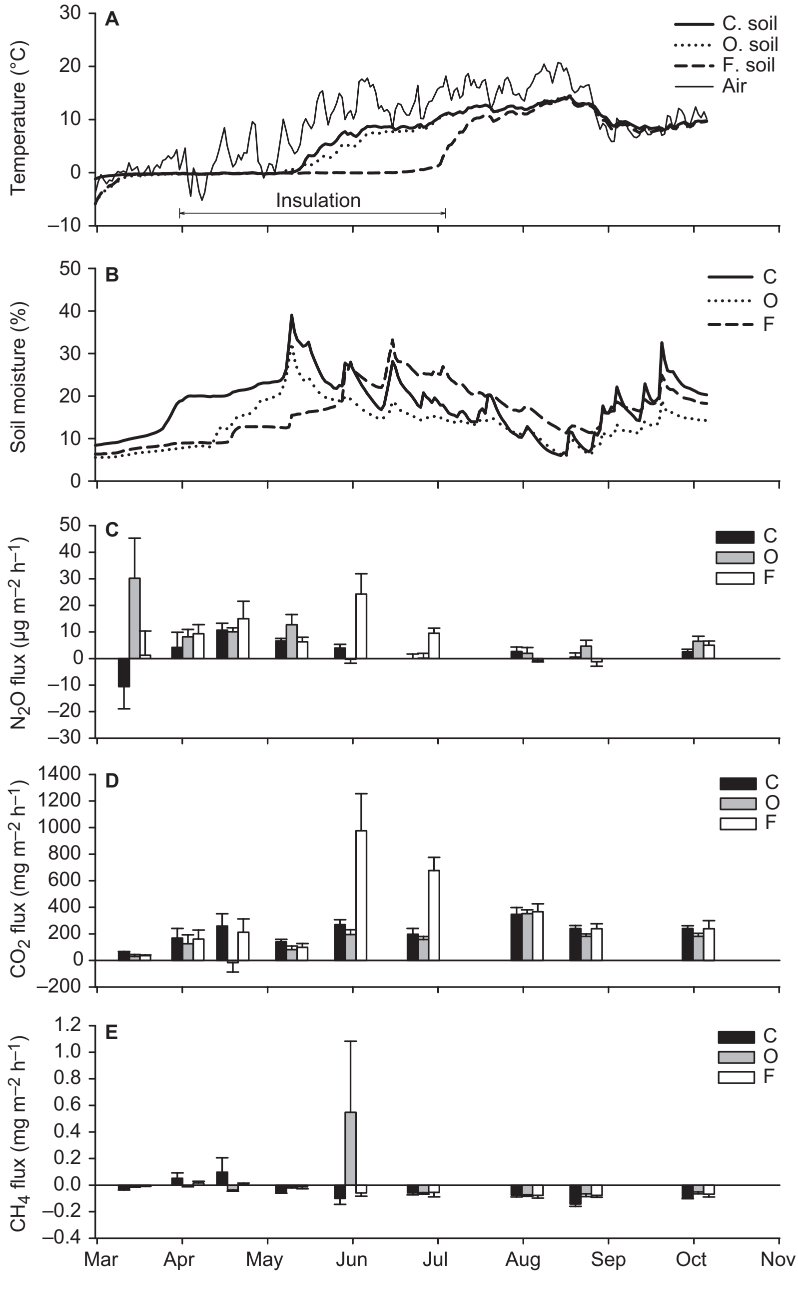

Fig. 1. (**A**) Mean daily air and soil temperatures at a depth of 15 cm, (**B**) soil volumetric moisture content at the depth of 15 cm, (**C**) N_2O flux, (**D**) CO_2 production, and (**E**) CH_4 flux during the period from March to October 2007. Treatments: C = control, O = open, F = delayed soil frost thawing. Bars are the mean emissions from replicate sampling points (*n* = 6), and the error bars show the standard error of the mean. A plus sign is emission, and a minus sign uptake of the gas from the atmosphere into the soil.

between the gas fluxes and the environmental variables (SPSS 14.0).

Results

Soil physical and chemical properties

The treatments had an effect on soil moisture and soil temperature (Fig. 1). Thawing started in the C and O treatments in the beginning of May, while in the F treatment the soil temperature at 15 cm depth remained close to 0 °C until the end of June (Fig. 1). The mean soil temperature during the 202-day period (from spring to autumn) was the highest in the C treatment and the lowest in the F treatment (Table 1). Soil moisture in the C and B treatments was the highest after snow melt in early May, whereas in the F treatment it reached a peak in the middle of June (Fig. 1). However, the C and F treatments had similar mean soil moisture contents, both lower than that in the O treatment (Table 1).

During the winter following the snow manipulations, there was still a statistical difference ($p < 0.001$) in the soil temperature between the treatments. Soil temperature at the depth of 15 cm in the F treatment (mean –0.36 °C) differed from that in the O (–0.31 °C) and C treatments (–0.25 °C) between 9 January and 4 April 2008. Also the soil moisture content was the highest ($p < 0.001$) in the C treatment (mean 14.4%), lower in the F treatment (10.9%) and the lowest in the O treatment (9.70%).

In June 2007, the NO_3^- concentrations were the lowest in the C and O treatments (< 0.07 μg g^{-1}), but significantly higher in the F treatment (0.28 μg g^{-1} and 0.21 μg g^{-1} for the humus and mineral soil, respectively) (Table 1). In October, the NO_3^- concentration was low in all the treatments. NO_2^- was not detected in any of the samples. The NH_4^+ concentrations in the organic horizon were lower in the C (< 2.5 μg g^{-1}) than in the O or F treatments, and there was no significant difference between the sampling times. In the mineral soil, the NH_4^+ concentrations were higher in June than in October in all the treatments.

Gas dynamics

In March 2007, the control soil had a negative N_2O flux indicating uptake of this gas, whereas N_2O was emitted from the O and F treatments. From April to late June (insulation on the F plots) N_2O was emitted from the control and treatments. During this period, the N_2O emissions from the F treatment were significantly ($p < 0.001$) higher than those from the control. From August to October, the mean N_2O emissions were similar in all treatments (Fig. 1). The N_2O emissions correlated negatively with soil temperature, i.e. the emissions increased with decreasing temperature (Table 2 and Fig. 2). The highest N_2O emissions occurred when the soil temperature at the depth of 5 cm was close to 0 °C. There was no correlation between soil moisture content and the N_2O fluxes (Table 2).

In March 2007, the soil CO_2 production was low in all the treatments. In late June (end of the insulation period), the CO_2 production rate in the F treatment was three-fold that in the other treatments, even though the soil temperature (depth 5 cm) in the F treatment remained close to 0 °C. However, there was no significant difference in the CO_2 production rates between the treatments during the whole insulation period. From August to October the CO_2 production rates were close to those in the early spring, and at a similar rate

Table 1. Cumulative fluxes of N_2O and CH_4 and the mean soil CO_2 production rate during the period from 15 March to 2 October 2007 (202 days) in the control (C), open (O) and prolonged frost treatments (F). The NO_3^- and NH_4^+ concentrations in the 0–3 cm organic horizon (OH) and 3–10 cm uppermost mineral soil layer (ML) were measured in June and in October. Mean soil temperatures at depths of 5, 15 and 50 cm and volumetric moisture content (VM) were measured continuously.

	N_2O (kg ha^{-1})	CH_4 (kg ha^{-1})	CO_2 (mg m^{-2} h^{-1})	NO_3^- (μg g^{-1})		NH_4^+ (μg g^{-1})		$T_{-5\ cm}$ (°C)	$T_{-15\ cm}$ (°C)	$T_{-50\ cm}$ (°C)	VM (%)
				June	Oct.	June	Oct.				
C	0.13	–1.6	201					7.76	7.01	6.16	19
C_{OH}				0.002	0.000	3.1	2.5				
C_{ML}				0.004	0.008	0.91	0.19				
O	0.27	–1.1	134					7.56	6.48	5.24*	12*
O_{OH}				0.002	0.000	5.2	5.3				
O_{ML}				0.007	0.008	0.82	0.18				
F	0.31	–2.2	313					5.24**	4.38**	3.60**	19
F_{OH}				0.28*	0.00	4.6	4.9				
F_{ML}				0.21*	0.02	0.92	0.08				

*$p < 0.05$, **$p < 0.01$ (significant difference from the control).

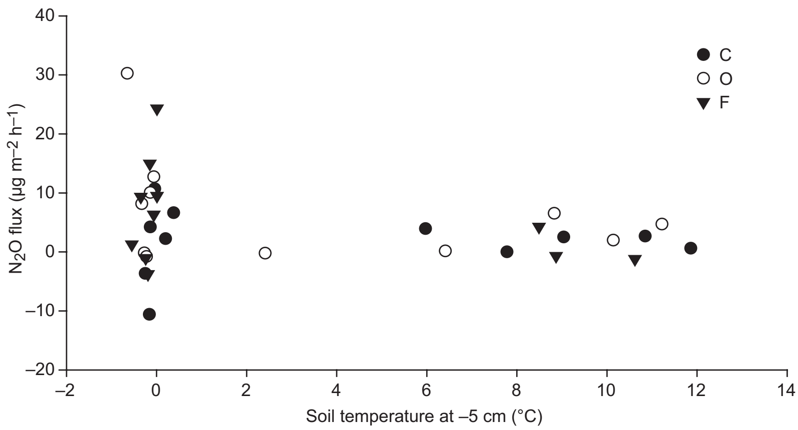

Fig. 2. Average daily N_2O fluxes from the forest floor (C = control, O = open, F = delayed frost) plotted against soil temperature at the depth of 5 cm during the period March to October 2007.

in all the treatments. The soil CO_2 production rate increased with increasing soil temperature in all the treatments, but it did not correlate with the soil moisture content (Table 2).

In April, the C and F treatments had low CH_4 emissions, and thereafter they were net CH_4 sinks. The O treatment was a net sink for CH_4 in March and April, but emitted CH_4 in late May (Fig. 1). From August to October, all the treatments were sinks for CH_4 and the uptake rate increased with increasing soil temperature in all the treatments, but it did not correlate with soil moisture (Table 2).

Cumulative emissions

During the 202-day period between March 15 and October 2 the cumulative N_2O emission from the C treatment was about one half that from the O and F treatments (Table 1). However, there were no statistically significant differences in the N_2O emissions between C and the other treatments. The CO_2 production rates were higher in the F than in the O treatments (p = 0.025), but there was no statistically significant difference between the treatments and the control. Even though there were occasionally some CH_4 emissions, all the treatments were net sinks for CH_4 over the whole study period (Table 1).

In the measurements carried out during the winter 2008, one year after the manipulations had been started, there were no differences in the gas flux rates between the treatments. In the period from January to 4 April 4, the soils were sinks for N_2O and CH_4, with mean rates of –1.14 μg m^{-2} h^{-1} and –0.006 mg m^{-2} h^{-1}, respectively. A rough estimate of the annual emission of N_2O from the control site would therefore be 0.09 kg N_2O ha^{-1}. During the winter period the soil was a consumer of CH_4, and the estimated annual net emission would be –1.9 kg CH_4 ha^{-1} from the control plots. The soil CO_2 flux during winter 2008 was low, on the average 37 mg m^{-2} h^{-1}.

Table 2. Spearman Rank Correlation coefficients between the mean N_2O and CH_4 fluxes, CO_2 production, and the environmental variables (n = 27) (*p < 0.05, **p < 0.01). The CH_4 flux is expressed as uptake (CH_4 flux from the atmosphere to the soil is positive). VM is the volumetric soil moisture content at a depth of 15 cm. $T_{-5\text{ cm}}$, $T_{-15\text{ cm}}$ and $T_{-50\text{ cm}}$ are soil temperatures at depths of 5, 15 and 50 cm, respectively.

	N_2O	CO_2	CH_4	VM	$T_{-5\text{ cm}}$	$T_{-15\text{ cm}}$
CO_2	–0.292					
CH_4	–0.410*	0.682**				
VM	0.138	0.328	0.067			
$T_{-5\text{ cm}}$	–0.470*	0.744**	0.794**	0.101		
$T_{-15\text{ cm}}$	–0.468*	0.716**	0.785**	0.088	0.988**	
$T_{-50\text{ cm}}$	–0.485*	0.687**	0.801**	0.056	0.974**	0.983**

Gas concentrations under the insulation cover

The CO_2 and N_2O concentrations were higher under the insulation cover applied between 28 March and 4 July (1500–5000 ppm for CO_2 and 1.1–0.4 ppm for N_2O) than the ambient concentrations (380 ppm for CO_2 and 0.32 ppm for N_2O) in April, but close to the ambient concentrations in May. The CH_4 concentrations remained close to the ambient (1.8 ppm) in all the samples.

Discussion

Upland forest soils in Finland are subjected to low N deposition and are nitrogen limited, which may explain the earlier observed low N_2O emissions. In our study, the N_2O emissions during the summer months were higher than those reported for some pine forests in Finland (Maljanen *et al.* 2006a, Pilegaard *et al.* 2006), but slightly lower than those measured in a spruce forest in Finland (Maljanen *et al.* 2006b). The mean N_2O emission from the control area, 2 μg N_2O m^{-2} h^{-1}, was similar to that estimated by Brumme *et al.* (2005) for boreal forest soils, 2.2 μg N_2O m^{-2} h^{-1}. However, the mean emissions from the manipulated soils (8.3 and 7.7 μg N_2O m^{-2} h^{-1}) were close to the mean emission level for temperate forests, 13 μg N_2O m^{-2} h^{-1} (Brumme *et al.* 2005).

In our study, prolonged soil frost increased the soil NO_3^- concentration in winter and early summer, and also increased the N_2O emissions. Evidently, the soil in boreal spruce forests has more favourable chemical/physical properties for nitrogen mineralization and associated nitrification and denitrification than the soil in pine forests. A low soil temperature in winter further enhances the processes related to N_2O production in the soil in spruce forests. Spruce stands generally grow on more fertile sites than pine stands, which would explain this difference. Another factor is the effective extinction of light by the dense spruce canopy that results in a sparse field layer vegetation, potentially reducing nitrogen uptake by vascular plants when only the soil surface layer has thawed and the deeper tree roots are still inactive.

At the end of the insulation period the CO_2 production rate in the F treatment was high. The enhanced emissions of both N_2O and CO_2 after the insulation period could be partially related to the release of trapped gases during thawing (Goodroad and Keeney 1984, van Bochove *et al.* 2001), and not only to the high availability of organic C and N and increased microbial activity (e.g. Christensen and Tiedje 1990). The insulation cover could also reduce evaporation and create higher soil moisture conditions, thereby favouring denitrification which is probably the main mechanism for N_2O production in soils close to 0 °C (Mørkved *et al.* 2006, Öquist *et al.* 2007). At low soil temperatures, the N_2O production rate can be limited by NO_3^- availability (Mørkved *et al.* 2006, Öquist *et al.* 2007). In our study, there was NO_3^- production at the lowest temperature (F treatment) during the insulation period, which is consistent with the findings of earlier studies that have shown some NO_3^- production in soil at low temperatures (Groffman *et al.* 2001). The higher N availability in the F treatment could also be related to the lower N uptake by plants under the insulation cover.

The N_2O emission from the control soil during the 202-day period of was 0.13 kg ha^{-1}. After the treatment period the winter measurements in 2008 (from January 9 to April 4) showed a N_2O uptake rate similar to that in the control soil in winter 2007. The uptake of N_2O in the control soil (N_2O concentration in snow is below the ambient atmospheric concentration or decreasing N_2O concentration in chambers) is probably a result of N_2O reduction to N_2 by denitrification in the wet organic surface layer of the soil (Jassal *et al.* 2008). On the plots where the snow was removed, the organic layer was probably inundated with frozen water, whereas under the snow cover there was more unfrozen water in the soil thereby allowing N_2O reduction to take place. N_2O uptake in boreal forest soil during winter is opposite to the situation in boreal agricultural soils, where high N_2O emissions occur during winter (e.g. Syväsalo *et al.* 2004). The estimated annual N_2O emission for the control plots of 0.09 kg N_2O ha^{-1} is lower than the mean annual value of 0.43 kg N_2O ha^{-1} reported for boreal soils by Brumme *et al.* (2005), and is mainly the result of N_2O uptake during winter. Brumme *et al.* (2005)

assumed that boreal forest soils emit N_2O during the whole winter period at a rate equivalent to 40% of the annual emissions. However, the lack of continuous flux data makes it difficult to make reliable estimates of the annual N_2O emissions from northern soils. Annual emissions from the soil in the O and F treatments cannot be estimated due to the lack of winter data. However, our results show that the lower soil temperature resulting from a thinner snow cover may affect N_2O fluxes and soil respiration.

The CH_4 uptake rate in our study was similar (e.g. Kasimir-Klemedtsson and Klemedtsson 1997, Saari *et al*. 1998, Brumme *et al*. 2005) or lower (Maljanen *et al*. 2006b) than that reported for other boreal forests. The snow and frost manipulation treatments did not significantly affect the CH_4 fluxes from the forest soil, thereby confirming the results by Groffman *et al*. (2006).

Conclusions

This study shows that a low temperature can induce N_2O emissions from boreal upland forest soil, which generally have low N_2O emissions. Global warming, which will probably reduce the duration and thickness of the snow cover, thereby causing deeper frost and prolonged low soil temperatures in early summer, could therefore increase the N_2O emissions from boreal forests. Prolonged soil frost may also enhance soil respiration after thawing. In contrast to N_2O, the CH_4 fluxes are less sensitive to a reduction in snow pack thickness and a lowering of soil temperatures.

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